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A novel knowledge database construction method for operation guidance expert system based on HAZOP analysis and accident analysis

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ABSTRACT

An expert system for operation guidance will contribute to identifying the operatoration problems and indicating the resolutions thereof, because the information stored in the expert system can be utilized to resolve the corresponding technical problems. However, there are several problems that should be solved in the practical application of the expert system, such as lack of corresponding knowledge or resolutions utilized to cope with the problems, inapplicable resolutions, too many resolutions for the operators to choose from to obtain the best one in the first time, etc. Obtaining and storing as much as information in the database of the expert system are important issues in the construction process of the expert system. The accident analysis results contain a limited number of accident cases and the HAZOP analysis only refers to a single deviation analysis. This paper has presented a novel knowledge database construction method for an operation guidance expert system based on the HAZOP analysis and the accident analysis, which can be used to resolve the above problems. The HAZOP analysis results are combined with the accident analysis results and the combination information can be stored in the database of the expert system, and can be employed to forecast accidents or identify accident causes. The structures of the operation guidance table and the accident investigation table have been illustrated. The residuum hydrotreating process expert system is taken as an example to illustrate the knowledge database construction method. With the aid of this expert system, the operators will well understand the operations and adopt the best resolutions to deal with the abnormal situations. Also the operators can identify potential risks existing in the plant which will result in accidents according to the accident analysis results associated with the HAZOP analysis results.

1. Introduction

Generally, an expert system, a computer program built for the diagnosing, fault-finding and problem-solving purposes, closely matches the human logic thinking process. The expert system is always composed of knowledge databases, inference engines, knowledge-acquiring regulations and human interfaces, etc. The information stored in the knowledge database could be employed to deduce new facts (Abacoumkin & Ballis, 2004; Liao, 2005). There are some expert systems which have been widely used in chemical process industries, such as the INTEMOR program (real-time intelligent monitoring and accident preventive systems), the PES program (petroleum production real-time analysis design expert system), etc., because human operations always play a tremendous role in running the plant and the operators need the corresponding guidance of the expert systems, especially in some complex process plants (Liao, 2005). Processes, human operations, pieces of equipment, materials, instruments, control systems, safety and environment, etc., interweave to form a complex process plant. In a complex process, many types of equipment are often operated at extremes of pressure and temperature, thus making them more vulnerable to equipment failures (Venkat, Zhao, & Shankar, 2000). And the operations are so complex that it is almost impossible for operators to identify all the abnormal situations and obtain the causes thereof in the first time (Wang, Gao, & Guo, 2009). One of the main functions of the expert system is to identify the problems of the operators and indicate the resolutions thereof. Therefore, where and how to obtain as much as information, which can be stored in the database of the expert system and can be utilized to resolve the corresponding technology problems, are important issues in the construction process of an expert system. Three problems often exist in the application of the expert system: (1) there is no corresponding knowledge or resolution utilized to cope with the problem; (2) the resolutions are not applicable; (3) the

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expert system provides several resolutions, but it is impossible for the operators to choose the best one in the first time.

A HAZOP analysis is a process risk analysis method, which can be employed to identify potential risks existing in the industry processes. In the HAZOP analysis process, P&IDs of the complex process plant should be examined by a multi-disciplinary team of experts systematically, and all conceivable deviations far from design intentions in the plant can be identified and all the possible abnormal causes and the adverse consequences of these deviations can be determined. The considerations of the experts are provided in the following four aspects: (1) determining whether a given operation or activity has the potential to give rise to a hazardous situation, (2) determining the range of hazardous events that the operation or activity could present (Jeong, Lee, Lee, & Lim, 2008), (3) identifying the routes by which each of these hazardous events could be understood, i.e., identifying the potential incident scenarios, (4) providing some prevention suggestions or measures to avoid hazardous events if the safeguards are not enough (Guimaraes & Lapa, 2006; Kim & Seong, 2006; Wu, Xia, & Zhang, 2003). An accident analysis is an important process which is mainly utilized to acquire accidents causes, consequences, safeguards, treatment measures, suggestions, prevention methods, etc. Many prevention measures could be adopted to avoid the accidents according to the accident analysis. The operators can well understand the accidents and adopt effective measures to deal with the abnormal situation according to the accident analysis results, especially the treatment measures.

It will be an enormous waste of expert efforts if the HAZOP analysis results and the accident analysis results are only utilized to identify the potential problems of the process plant design and memorize accident processes. The reports of the HAZOP analysis and the accident analysis can be considered as the knowledge resources of the expert system database, and the reasons include the following aspects: (1) as much as information, which can be utilized to assist the operators in dealing with problems or avoiding some accidents, is contained in the HAZOP analysis report, and can be amended so as to be stored in the expert system database; (2) the results of the HAZOP analysis and the accident analysis may include a large number of danger spread paths, wherein a spread path contains the variables and their causal relationships from the start variable to the end variable and the intermediate variables between them. Variables could be many process parameters, such as temperature, pressure, liquid level, etc. A danger spread path is employed to describe a spread process of a danger event. Therefore, spread paths analyzed by experts can be helpful for operators to understand the problems and determine resolutions thereof; (3) the HAZOP analysis results could be combined with the accident analysis results to forecast accidents or identify accident causes. Operators can acquire the primary causes and the deeply dangerous consequences of an abnormal situation caused by the fluctuation of a variable value, and can identify potential risks which will result in accidents, according to the HAZOP analysis results and the accident analysis results. Therefore, the HAZOP analysis results and the accident analysis results may be the most appropriate knowledge resources which can be utilized to construct the knowledge database of the expert system.

However, some accidents were caused by multiple causes, and the HAZOP analysis only refers to the single deviation analysis. The accident analysis results contain a limited number of accident cases while the accident analysis only pays attention to the accidents which have occurred.

Hence, this paper presents a novel knowledge database construction method for an operation guidance expert system based on the HAZOP analysis and the accident analysis. The knowledge database of the expert system is also an available inheritance instrument, which can be helpful for the experts to record their experience knowledge and can be subservient to the need of young operators. The reasons why the young operators need the operation guidance expert system are as follows: first of all, it is impossible for operators to acquire all the operation experience; then, the operators can not suffer all kinds of problems; what's more, skilled operators will be promoted to new positions or will retire; finally, many processes are novel processes and many problems are novel problems. Young operators should obtain sufficient experience knowledge which is more valuable than that of any others associated with the current analysis object to compensate for lack of engineering experience or expertise from the expert system. Therefore, the research of the construction method will play a significant role in the practical applications of the operation guidance expert system.

2. Knowledge database of the operation guidance expert system based on HAZOP analysis and accident analysis

2.1. Data of the operation guidance expert system based on HAZOP analysis and accident analysis

With the help of the operation guidance expert system, operators can identify the consequences of each single process variable and can determine accident causes, which are the two main functions of the operation guidance expert system. The knowledge database should contain at least two tables. One table can be called the operation guidance table, and the other is named the accident investigation table. Data of the two tables can be mainly obtained by the amended data of the HAZOP analysis reports and the accident analysis reports. In the operation guidance table, a piece of data should be composed of cause, process variable, spread path, consequence, safeguard, likelihood, severity, risk level, accident case, cause of the accident, process, treatment method, casualty, economical cost, environment effect, etc. And in the accident investigation table, a piece of data should be composed of accident case, accident cause, process, treatment method, casualty,

Table 1
One piece of data of the operation guidance table in the knowledge database.

C		**PV**			**SP**		
The temperature of propylene feed is higher than the design value		The temperature of the polymerization reactor			The temperature of propylene feed > The temperature of the polymerization reactor		
CO	**SA**	**L**	**S**	**R**	**AC**	**COA**	
Explosive polymerization	The flowrate of the hydrogen feed	3	3	2	Explosive polymerization in the polymerization reactor.	The heat cannot be carried out	
P		**TM**			**CAS**	**EC**	**EE**	**COM**
The feed temperature is too high and no emergency measures were adopted. The heat cannot be carried out. Explosive polymerization		The flowrate of the cooling water is increased and the pressure of the reactor was released			No injuries & no death	60,000 RMB	–	–

Table 2
One piece of data of the accident investigation table in the knowledge database.

AC	**COA**			**P**				
Explosive polymerization in the polymerization reactor	The heat cannot be carried out			The feed temperature is too high and no emergency measures were adopted. The heat cannot be carried out. Explosive polymerization				
TM	**CAS**	**EC**	**EE**	**C**	**PV**			
The flowrate of the cooling water is increased and the pressure of the reactor was released	No injuries & no deaths	60,000 RMB	–	The temperature of propylene feed is higher than the design value	The temperature of the polymerization reactor			
CO	**SP**			**SA**	**L**	**S**	**R**	**COM**
Explosive polymerization	The temperature of propylene feed > The temperature of the polymerization reactor			The flowrate of the hydrogen feed	3	3	2	–

economical cost, environment effect, cause, process variable, spread path, consequence, safeguard, likelihood, severity, risk level, etc.

2.2. Structure of the operation guidance expert system based on HAZOP analysis and accident analysis

Information of the HAZOP analysis results can be associated with the corresponding information of the accident analysis results, because they may contain the common components, i.e., the cause and the process variable. The information can be combined and stored in the operation guidance table and the accident investigation table.

In the operation guidance table, operators can acquire cause, process variable, spread path, consequence, safeguard, likelihood, severity, risk level, accident case, cause of the accident, process, treatment method, casualty, economical cost, environment effect, etc., according to the deviation of the process variable and the identified cause. And in the accident investigation table, operators can acquire accident case, accident cause, process, treatment method, casualty, economical cost, environment effect, cause, process variable, spread path, consequence, safeguard, likelihood, severity, risk level, etc.

The operation guidance table has been shown in Table 1 and the accident investigation table in Table 2. In Table 1, one piece of information of the HAZOP analysis of propylene polymerization has been associated with an explosive polymerization accident. With the help of the operation guidance information, the operator can obtain the consequence of deviation of the process variable, the accident case caused by the deviation, the treatment measures, etc. So the operator should make a decision and adopt appropriate operation procedures to deal with the abnormal situations. In Table 2, one cause of the accident case has been associated with a piece of HAZOP analysis information. And due to the assistant information, the operator can expressly know which parts of the plant he should pay more attention to and which prevention measures he should adopt to improve the intrinsic safety level of the plant.

The symbols and their meanings in Tables 1 and 2: C–cause; PV–process variable; SP–spread path; CO–consequence; SA–safeguard; L–likelihood; S–severity; R–risk level; AC–accident case; COA–cause of the accident; P–process; TM–treatment method; CAS–casualty; EC–economical cost; EE–environment effect; COM–comment.

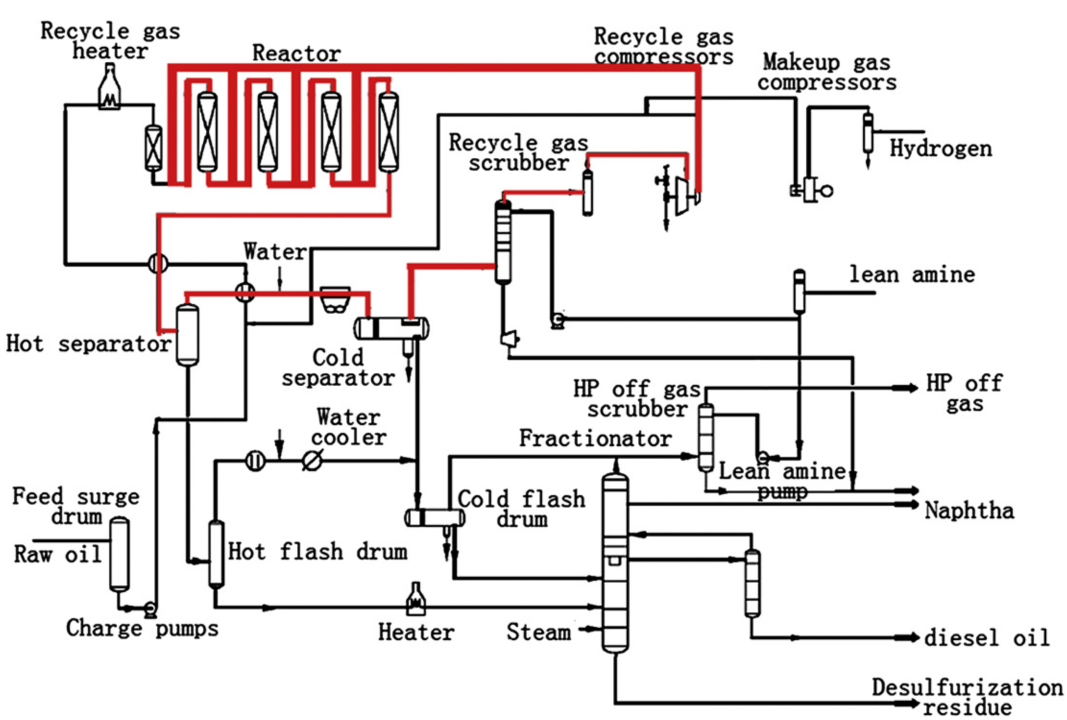

Fig. 1. The flowchart of the residuum hydrotreating process.

Table 3
Categorization of the causes of the explosion accidents in chemical process.

	Class	Kind
Physical explosion	1. The working pressure of the equipment exceeds its design pressure	1 High pressure gas rush into the low pressure equipment
		2 Sudden boiling
		3 High pressure liquid flashes
		4 Residual liquid is heated
		5 Pipe obstruction
		6 High pressure gas reverse flow
		7 Heating temperature is too high
		8 Steam pressure set value is too high
		9 Non condensable gas or inert gas is remaining in the equipment
		10 The production load is improved
		11 Large fluctuation of production load
		12 Adiabatic compression
	2. The pressure tolerance ability of equipment descend	13 Texture, structure, manufacture and so on
		14 Corrosion
		15 Abrasion
		16 Crack
		17 Fatigue
		18 External load
		19 Environment influence
Chemical explosion	3. The presence or generation of flammable and explosive chemical materials	20 Flammable material leak or explosive material leak
		21 Air rush into equipments
		22 Spray explosion
		23 Dust explosion
		24 Residual material in the equipment is flammable or explosive
		25 Equipment vibration or metal parts friction
		26 Fast burning
		27 Electrostatic influence
		28 The internal seal or packing is explosive and/or flammable
		29 Flammable and explosive chemical materials is generated in some subsidiary reaction
	4. The presence or generation of special flammable and explosive chemical materials	30 Photosensitive material
		31 Thermal sensitive material
		32 Strong oxidant
		33 Peroxide concentration
		34 Intense chemical reactions
	5. Accumulated energy cannot be released	35 Too much heat release
		36 Heating temperature rises too fast
		37 Heating temperature is too high
		38 Excess reactant
		39 High catalyst activity
		40 Intense chemical reactions
		41 Interruption or reduction of cooling water
		42 Uneven stirring
		43 The reaction rate is too fast
		44 The reaction time is too long
		45 The heating time is too long
		46 Uneven heating

2.3. Data acquisition

The data acquisition is an important section in establishment process of the knowledge database. The operation guidance table and the accident investigation table should be established according to the following procedures. First of all, the written materials, including the accident analysis reports, photos, accident reports, etc., should be collected; then, the names of accidents, process, treatment methods, casualty, economical cost, environment effect, etc., should be determined; what's more, cause, process variable, spread path, consequence, safeguard, likelihood, severity, risk level, comments can be obtained from the HAZOP analysis report; finally, the HAZOP analysis results can be associated with the corresponding accident analysis results and the data acquired should be stored in the operation guidance table and the accident investigation table. The HAZOP analysis results should be directly recorded into their respective fields in these two tables if the HAZOP analysis results cannot be associated with any other information of the accident case. The deviations should be analyzed by the HAZOP analysis groups and the results should be added to the HAZOP analysis reports if the accident analysis results cannot be associated with the HAZOP analysis results.

2.4. Illustrations of the accidents

The illustrations of the accidents can be utilized to express the potential dangers and the accidents. And the accident mechanism can be well understood by the operators. The accident figures can be obtained by the figure collections and figure drawings. The corresponding descriptions, accident photos, statistical tables, statistical charts, references, etc., should be associated with the corresponding accidents, and the expert system will exhibit the accident figures with the appropriate information if the operators log in the expert system and search for the operation guidance information and the accident investigation information.

3. Knowledge database construction method of residuum hydrotreating process expert system

3.1. Instruction of the residuum hydrotreating process

The plant of the residuum hydrotreating process mainly consists of a reaction section, a fractionation section, a gas desulfuration and a public project. Fig. 1 shows a simple flowchart of the residuum hydrotreating process (Zhu & Liu, 2000).

Table 4
Categorization of the poisoning accidents in chemical process.

Class	Harm to human	Invading paths	Representative toxic substances	Main symptoms
1. Acute poisoning	1.1. Respiratory system	1.1.1. Respiratory system	1.1.1.1. Gas CO, CS_2, Cl_2, H_2S, amine, chloromethyl methyl ether, phosgene, etc.	Emphysema, asphyxia, shock, etc.
			1.1.1.2. Liquid CH_3Br, $SiCl_4$, dimethyl sulfate, chromic acid, etc.	Emphysema, arrhythmia, renal failure, etc.
			1.1.1.3. Solid powder Cd, Mn, Be, P, CrO, etc.	Pneumonia, central nervous system damage, emphysema, arrhythmia, renal failure, etc.
	1.2. Nervous system	1.2.1. Respiratory system	1.2.1.1. Gas PH_3, etc.	Acute toxic encephalopathy
			1.2.1.2. Liquid tetraethyl lead, Hg, Sn, etc.	Central nervous system damage, emphysema, arrhythmia, renal failure, etc.
		1.2.2. Digestive system	1.2.2.1. Liquid C_6H_6, gasoline, CH_3Br, etc.	Emphysema, arrhythmia, renal failure, etc.
			1.2.2.2. Solid powder Tl, etc.	Alopecia, hypopsia, toxic hepatitis, etc.
		1.2.3. Skin	1.2.3.1. Gas HF, etc.	Emphysema, bronchitis, etc.
			1.2.3.2. Liquid chloroprene, etc.	Epileptoid convulsion hemolytic anemia, injury of the liver and heart, renal failure, etc.
			1.2.3.3. Solid powder Tl, etc.	Alopecia, hypopsia, toxic hepatitis, etc.
	1.3. Blood system	1.3.1. Respiratory system	1.3.1.1. Gas H_2S, CCl_4, SO_2, H_3As, etc.	Raising of the number of the leukocytes, hemoglobin deformation, raising of the number of the leukocytes, hemolytic anemia, etc.
			1.3.1.2. Liquid aniline, etc.	Hypoxia, central nervous system damage, etc.
			1.3.1.3. Solid powder trinitrotoluene, Pt, Cr, etc.	Disorders of lents, liver injury, emphysema, arrhythmia, renal failure, etc.
		1.3.2. Digestive system	1.3.2.1. Liquid acrylonitrile, nitrobenzene, etc.	Hemolytic anemia, injury of the liver and heart, renal failure, emphysema, asphyxia, shock, etc.
			1.3.2.2. Solid powder trinitrotoluene, phenylhydrazine, etc.	Disorders of lents, liver injury, emphysema, arrhythmia, renal failure, etc.
		1.3.3. Skin	1.3.3.1. Gas HF, etc.	Emphysema, bronchitis, etc.
			1.3.3.2. Liquid chloroprene, nitrobenzene, etc.	Epileptoid convulsion hemolytic anemia, injury of the liver and heart, renal failure, etc.
			1.3.3.3. Solid powder Tl, etc.	Alopecia, hypopsia, toxic hepatitis, etc.
	1.4. Urinary system	1.4.1. Respiratory system	1.4.1.1. Gas AsH_3, etc.	Renal failure, etc.
			1.4.1.2. Liquid CCl_4, C_6H_6, etc.	Emphysema, asphyxia, shock, etc.
		1.4.2. Digestive system	1.4.2.1. Liquid CCl_4, ethylene glycol, etc.	Uremia, emphysema, asphyxia, shock, etc.
			1.4.2.2. Solid powder Sn, U, Tl, etc.	Gastrointestinal ileus, etc.
		1.4.3. Skin	1.4.3.1. Liquid ethylene glycol, etc.	Uremia, etc.
			1.4.3.2. Solid powder Tl, etc.	Alopecia, hypopsia, toxic hepatitis, etc.
	1.5. Circulatory system	1.5.1. Digestive system	1.5.1.1. Liquid CCl_4, Hg, trichloroethylene, C_6H_6, gasoline, etc.	Myocardial damage, emphysema, arrhythmia, renal failure, etc.
			1.5.1.2. Solid powder Ti, As, P, $BaCl_2$, etc.	Arrhythmia, myocardial damage, respiratory muscle paralysis, emphysema, arrhythmia, renal failure, etc.

(*continued on next page*)

Table 4 (*continued*)

Class	Harm to human	Invading paths	Representative toxic substances	Main symptoms
		1.5.2. Skin	1.5.2.1. Liquid CCl_4, Hg, gasoline, etc.	Myocardial damage, emphysema, bronchitis, etc.
			1.5.2.2. Solid powder Ti, As, P, $BaCl_2$, etc.	Arrhythmia, myocardial damage, respiratory muscle paralysis, emphysema, arrhythmia, renal failure, etc.
		1.5.3. Respiratory system	1.5.3.1. Gas CS_2, HF, etc.	Cor pulmonale, etc.
			1.5.3.2. Liquid trichloroethylene, C_6H_6, etc.	Arrhythmia, etc.
	1.6. Digestive system	1.6.1. Digestive system	1.6.1.1. Liquid CCl_4, nitrobenzene, etc.	Uremia, emphysema, asphyxia, shock, etc.
			1.6.1.2. Solid powder As, Pt, P, Ti, TNT, etc.	Acute gastroenteritis, disorders of lents, liver injury, etc.
		1.6.2. Respiratory system	1.6.2.1. Gas $CHCl_3$, etc.	Toxic hepatitis, etc.
			1.6.2.2. Liquid CCl_4, etc.	Emphysema, arrhythmia, renal failure, etc.
		1.6.3. Skin	1.6.3.1. Liquid CCl_4, etc.	Emphysema, arrhythmia, renal failure, etc.
			1.6.3.2. Solid powder trinitrotoluene, etc.	Disorders of lents, liver injury, etc.
2. Chronic poisoning	2.1. Respiratory system	2.1.1. Respiratory system	2.1.1.1. Gas Cl_2, NO_x, etc.	Disease of respiratory system, etc.
			2.1.1.2. Liquid epichlorohydrin, HCl, CH_3Br, etc.	Perforation of nasal septum, emphysema, arrhythmia, renal failure, etc.
	2.2. Nervous system	2.2.1. Respiratory system	2.2.1.1. Gas Cl_2, CH_2O, etc.	Neurasthenia, etc.
			2.2.1.2. Liquid tetraethyl lead, CS2, chloroprene, styrene, etc.	Brain edema, hepatic encephalomyelopathy, emphysema, arrhythmia, renal failure, etc.
			2.2.1.3. Solid powder Pt, Hg, Mn, As, etc.	Emphysema, arrhythmia, renal failure, etc.
		2.2.2. Digestive system	2.2.2.1. Liquid tetraethyl lead, CS2, chloroprene, styrene, acetone, etc.	Brain edema, hepatic encephalomyelopathy, emphysema, arrhythmia, renal failure, etc.
			2.2.2.2. Solid powder Tl, As, Pt, Hg, Mn, trinitrotoluene, etc.	Acute gastroenteritis, disorders of lents, liver injury, emphysema, arrhythmia, renal failure, disorders of lents, liver injury, etc.
		2.2.3. Skin	2.2.3.1. Liquid tetraethyl lead, CS2, chloroprene, styrene, acetone, etc.	Brain edema, hepatic encephalomyelopathy, emphysema, arrhythmia, renal failure, etc.
			2.2.3.2. Solid powder Tl, etc.	Alopecia, hypopsia, toxic hepatitis, etc.
	2.3. Blood system	2.3.1. Respiratory system	2.3.1.1. Gas AsH_3, etc.	Hemolytic anemia, etc.
			2.3.1.2. Liquid C_6H_6, phenylhydrazine, etc.	Aplastic anemia, emphysema, asphyxia, shock, disorders of lents, liver injury, etc.
		2.3.2. Digestive system	2.3.2.1. Liquid C_6H_6, phenylhydrazine, etc.	Emphysema, asphyxia, shock, disorders of lents, liver injury, etc.
			2.3.2.2. Solid powder nitrobenzene, etc.	Hemolytic anemia, asphyxia, shock, disorders of lents, liver injury, etc.
		2.3.3. Skin	2.3.3.1. Liquid C_6H_6, phenylhydrazine, etc.	
			2.3.3.2. Solid powder nitrobenzene, U and other radioactive material, etc.	Hemolytic anemia, emphysema, asphyxia, shock, disorders of lents, liver injury, etc.
	2.4. Urinary system	2.4.1. Respiratory system	2.4.1.1. Gas	Toxic nephropathy, etc.

		AsH_3, etc.	
		2.4.1.2. Liquid CCl_4, C_6H_6, etc.	Emphysema, arrhythmia, renal failure, etc.
	2.4.2. Digestive system	2.4.2.1. Liquid CCl_4, C_6H_6, ethylene glycol, etc.	Emphysema, arrhythmia, renal failure, etc.
		2.4.2.2. Solid powder Sn, U, Tl, Cr, etc.	Emphysema, asphyxia, shock, disorders of lents, liver injury, etc.
	2.4.3. Skin	2.4.3.1. Liquid ethylene glycol, etc.	Uremia, etc.
		2.4.3.2. Solid powder Tl, Cr, etc.	Alopecia, hypopsia, toxic hepatitis, etc.
2.5. Motion system	2.5.1. Respiratory system	2.5.1.1. Gas F_2, etc.	Skeletal lesions, etc.
	2.5.2. Digestive system	2.5.2.1. Liquid vinyl chloride, metoclopramide, etc.	Parkinson, etc.
		2.5.2.2. Solid powder Cd, P, etc.	Toxic nephropathy
	2.5.3. Skin	2.5.3.1. Liquid vinyl chloride, etc.	Hypotension, asphyxia, shock, etc.
		2.5.3.2. Solid powder Cd, P, etc.	Pneumonia, emphysema, arrhythmia, renal failure, etc.
2.6. Digestive system	2.6.1. Digestive system	2.6.1.1. Solid powder Tl, Ti, etc.	Toxic hepatitis, etc.

The plant of the residuum hydrotreating process is one of the most dangerous plants in chemical industry. Firstly, many types of equipment are often operated at extremes of pressure and temperature, which makes them more vulnerable to equipment failures. Secondly, the operations are so complex that it is almost impossible for operators to identify all the abnormal situations and obtain the causes thereof in the first time. For example, a hydrogenation unit reaction system mainly consists of high-pressure heat exchangers, coolers, five reactors, one furnace, one H_2S desulfurization tower, etc. The system pressure drop is an important parameter. According to a process alarm, it is very difficult for the operators to obtain the root causes of the abnormal system pressure drop situation, because the system pressure drop can be influenced by a variety of process parameters, such as the outlet pressure of the compressor, the pressure of the reactor, the pressure of the cold separator and the pressure of the hot separator, etc. Unfortunately, these parameters can also be influenced by the pressure of the system. It has been proved that ascertaining the appropriate system pressure drop should not only be important for the equipment selection, especially for the compressor selection, but also plays a powerful role in the steady operation, the safety production and the energy saving, etc. The system pressure drop can be acquired by the calculation of the pressure drop of the circulating H_2 gas flowing through the whole reaction system, and

Table 5
Categorization of the human errors in chemical process.

	Class	Kind
Objective cause	1. Equipment failure	1 The material of the valve is erodible
		2 The material of the valve is corrodible
		3 The necessary torque of the valve is great
		4 Incorrect instructions or directions
		5 Error indication facilities
	2. Management error	6 Operation guidance is unavailable
		7 Operation guidance is inappropriate
		8 Lack of operation management
		9 Incorrect judgments
		10 Malpractice
		11 The command is unavailable
	3. System and environment	12 Bad weather
		13 Thermal radiation sources
		14 Vibration
		15 External impact
		16 Noise
		17 Geological disaster
		18 Power off
Subjective cause	4. Operation error	19 Operate frequently
		20 Forget to close
		21 Fail to open
		22 Forget to open
		23 Fail to close
		24 Turn the valve up
		25 Turn the valve down
		26 Changes flowrate too rapidly
		27 Changes flowrate too slowly
		28 Close the valve too slowly
		29 Open the valve too early
		30 Open the valve too lately
		31 Close the valve too early
		32 Close the valve too lately

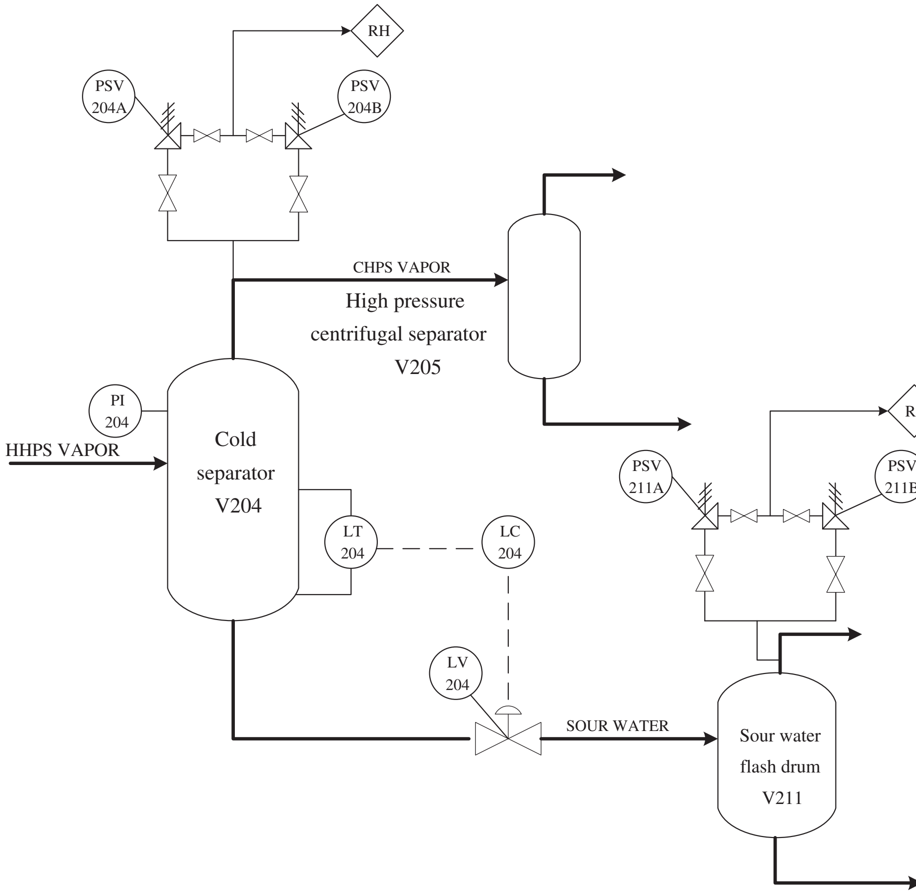

Fig. 2. The flowchart of the HHPS separation system.

the H_2 flow route has been drawn up in Fig. 1. Generally, the pressure drop of the furnace is approximately 0.6 MPa, and the pressure drop of each reactor bed is about 0.1 MPa which could be calculated according to the catalyst packing style. The pressure values of most of the coolers and heat exchangers could be set near 0.1 MPa. In the industry production, the operators always improve the flowrate of the gas to eliminate or decrease the coke which was generated in the heater exchanger and reactors, and monitor the system pressure drop. The catalyst of the reactors will be replaced and refreshed if the value of the system pressure drop exceeds the limit. But using these safeguards to ensure the production safety has not changed the reality that the system pressure drop would be verifying all the time. Thirdly, there are a variety of risk factors in the process, and it is very difficult to control the strongly exothermic reaction while the plant is in an abnormal situation. Therefore, an operation guidance expert system has been regarded as a necessary assistant for the operators.

3.2. Accident cause classification

The accident cause classification can contribute to the cause enumeration in the HAZOP analysis and the accident cause investigation, and it also will contribute to the combination of the HAZOP analysis results and the accident analysis results. The classification tables of accident causes of explosion, fire, toxic release, occupational disease, etc., can be established according to expert experience. The causes of accidents can be summarized and classed in several classes or kinds. Table 3 shows the cause classifications of the explosion accidents in chemical process (Wang, Gao, & Liu, 2008; Cui, 2006a, 2006b). Human error can be considered as the main cause of a number of accidents. The categorization of the poisoning accidents in the chemical process is shown in Table 4 and the category of the human errors in the chemical process is shown in Table 5 (Wang et al., 2009). Detailed classification of the accident causes would facilitate the combination of the HAZOP analysis results and the accident analysis results of the residuum hydrotreating process.

3.3. Combination of the information

3.3.1. Mechanism of a potential accident

(1) Simple flowchart of the HHPS separation system

The cold separator V204 is a high pressure device, and the sour water flash drum V211 is a low pressure device. And a simple flowchart of the HHPS separation system has been shown in Fig. 2.

(2) Potential hazard analysis

Causes

(1) The feed flowrate of the V204 is too low.
(2) Liquid leaks from the LV204.
(3) Liquid level control system fails or occurs error indication.

Consequence

High pressure gas rushes into the low pressure equipment V211 if the V204 is empty, and an explosion accident will take place.

Table 6
The data of the operation guidance table in the knowledge database.

No.1

C	PV	SP
The liquid level of the cold separator V204 is too low	The liquid level of the cold separator V204	The feed flowrate of the V204 > The liquid level of the V204 > The pressure of the soul water flash drum V211

CO	SA	L	S	R	AC	COA
Explosion accident	LC204; PSV204; PI204	4	3	3	Explosion accident	High pressure gas rushes into the low pressure equipment V211

P	TM	CAS	EC	EE	COM
The feed flowrate is too small and the liquid level of the V204 decreased. High pressure gas rushes into the low pressure equipment V211	The pressure of pressure equipment was released	No injuries & no death	400,000 RMB	Heavy pollution	–

No.2

C	PV	SP
The pressure of the feed of the cold separator V204 is too high	The pressure of the cold separator V204	The feed pressure of the V204 > The pressure of the cold separator V204

CO	SA	L	S	R	AC	COA
Explosion accident	PSV204; PI204	2	4	2	Explosion accident	The pressure of the feed of the cold separator V204 is too high, and the relief valve PSV204 can not work

P	TM	CAS	EC	EE	COM
The relief valve PSV204 can not work when the pressure of the cold separator V204 is higher than the design pressure of it	Cutting off the feed of the cold separator V204	No injuries & no death	1,000,000 RMB	Heavy pollution	–

No.3

C	PV	SP
The liquid level of the cold separator V204 is too low	The liquid level of the cold separator V204	The feed flowrate of the V204 > The liquid level of the V204 > The pressure of the soul water flash drum V211

CO	SA	L	S	R	AC	COA
Explosion accident	LC204; PSV204; PI204; PSV211	2	4	2	Explosion accident	High pressure gas rushes into the low pressure equipment V211, and the relief valve PSV211 can not work

P	TM	CAS	EC	EE	COM
The feed flowrate is too small and the liquid level of the V204 decreased. High pressure gas rushes into the low pressure equipment V211,but the relief valve PSV211 of the low pressure equipment V211 can not work	Cutting off the feed of the HHPS separation system and release the pressure of pressure equipment	No injuries & no death	900,000 RMB	Heavy pollution	–

Safeguards

(1) The control valve LV204 will adjust the valve degree automatically.
(2) The relief valve will release the pressure of the system.

3.3.2. Operation guidance table and accident investigation table of the residuum hydrotreating process

Three pieces of data of the operation guidance table of the residuum hydrotreating process have been shown in Table 6 and three pieces of data of the accident investigation table are shown in Table 7. The analysis result can be stored in these two tables. With these tables, the operators can obtain all possible causes which can result in the increase of the pressure of the system mentioned in the Section 3.1, and thus the operators may infer the most possible cause of the abnormal situation.

3.3.3. Operation guidance interface of the expert system of the residuum hydrotreating process

(1) Operation guidance interface

The operation guidance interface of the expert system of the residuum hydrotreating process is shown in Fig. 3.

(2) Acquiring the operation guidance information

The information of the explosion accident of the HHPS separation system has been summarized and recorded into the database of the expert system. The operators can select a process variable and a deviation, such as ‘The liquid level of the cold separator V204’ and ‘Flowrate + Low’, and can log in this interface as shown in Fig. 3. The names of the accidents which may be caused by the above process variable and deviation will be listed in the lower right corner of the interface. The operators can click on the pull-down menu button, and thus they can select and click on their interested accident name. Then the selected accident name will be shown in the top left corner of the interface, and all the information belonging to the selected accident name will be shown in the ‘Accident analysis’ field. Therefore, the operators can acquire the prior knowledge containing the causes, the process, the treatment methods, etc. The knowledge in the operation guidance interface will contribute to the understanding of the operation for the operators.

(3) Acquiring the accident investigation information

The accident investigation interface has the same structure with the operation guidance interface. People can select the interested accident name, and can log in the accident investigation interface.

Table 7
The data of the accident investigation table in the knowledge database.

No.1	
AC	Explosion accident of the HHPS separation system
COA	High pressure gas rushes into the low pressure equipment V211
P	The feed flowrate is too small and the liquid level of the V204 decreased. High pressure gas rushes into the low pressure equipment V211
TM	The pressure of pressure equipment was released
CAS	No injuries & no death
EC	400,000 RMB
EE	Heavy pollution
C	The liquid level of the cold separator V204 is too low
PV	The liquid level of the cold separator V204
CO	Explosion accident
SP	The feed flowrate of the V204 > The liquid level of the V204 > The pressure of the soul water flash drum V211
SA	LC204; PSV204; PI204; PSV211
L	4
S	3
R	3
COM	–

No.2	
AC	Explosion accident of the HHPS separation system
COA	The pressure of the feed of the cold separator V204 is too high, and the relief valve PSV204 can not work
P	The relief valve PSV204 can not work when the pressure of the cold separator V204 is higher than the design pressure of it
TM	Cutting off the feed of the cold separator V204
CAS	No injuries & no death
EC	1,000,000 RMB
EE	Heavy pollution
C	The pressure of the feed of the cold separator V204 is too high
PV	The pressure of the cold separator V204
CO	Explosion accident
SP	The feed pressure of the V204 > The pressure of the cold separator V204
SA	PSV204; PI204
L	2
S	4
R	2
COM	–

No.3	
AC	Explosion accident of the HHPS separation system
COA	High pressure gas rushes into the low pressure equipment V211, and the relief valve PSV211 can not work
P	The feed flowrate is too small and the liquid level of the V204 decreased. High pressure gas rushes into the low pressure equipment V211,but the relief valve PSV211 of the low pressure equipment V211 can not work
TM	Cutting off the feed of the HHPS separation system and release the pressure of pressure equipment
CAS	No injuries & no death
EC	900,000 RMB
EE	Heavy pollution
C	The liquid level of the cold separator V204 is too low
PV	The liquid level of the cold separator V204
CO	Explosion accident
SP	The feed flowrate of the V204 > The liquid level of the V204 > The pressure of the soul water flash drum V211
SA	LC204; PSV204; PI204; PSV211
L	2
S	4
R	2
COM	–

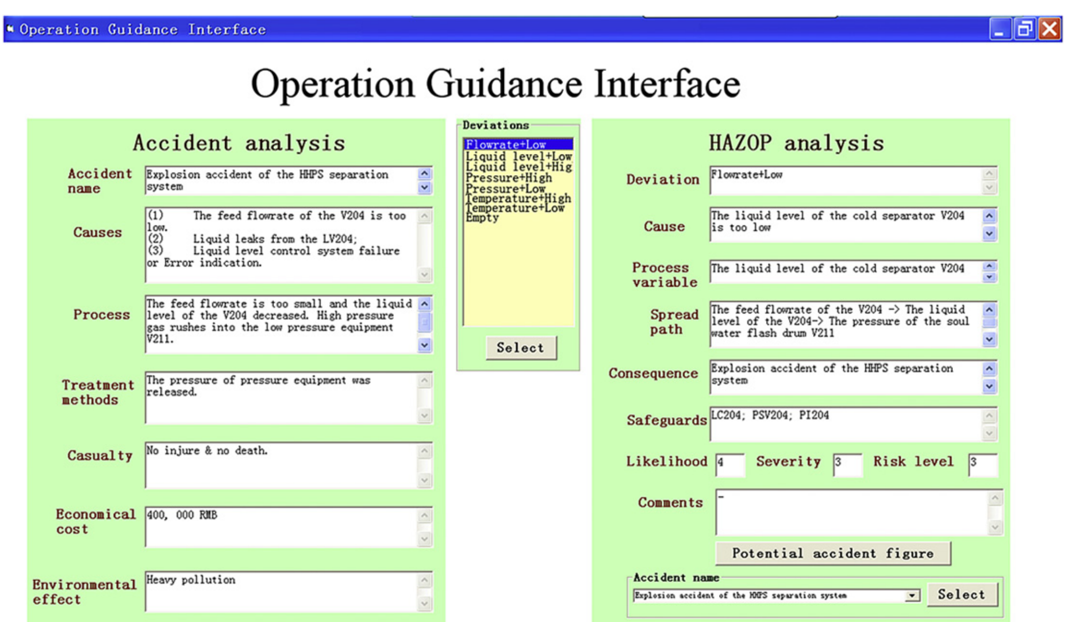

Fig. 3. The operation guidance interface of the expert system of the residuum hydrotreating process.

The accident causes will be shown in the ‘deviation’ field. People can select the interested deviation and the same accident name listed in the lower right corner of the interface. Then the corresponding HAZOP analysis information will be exhibited in the ‘HAZOP analysis’ field. The spread process, consequence, safeguard, likelihood, severity, risk level, potential accident figure, etc., relative to the deviation could be acquired.

4. Conclusions

The operation guidance table and the accident investigation table can be established to store the combination information. The HAZOP analysis results and the accident analysis results can be combined and stored in the database of the expert system. The operation guidance expert system can be employed to identify the problems of the operators and provide the resolutions of the problems to the operators. With the aid of the expert system, the probability of the human errors caused by the lack of experience can be reduced. However, due to the change of the design intentions of the plant, the HAZOP analysis results and the accident analysis results may be renewed, and thus the knowledge stored in the database should be updated according to the practical situations and the expert experience.

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References

Abacoumkin, C., & Ballis, A. (2004). Development of an expert system for the evaluation of conventional and innovative technologies in the intermodal transport area. *European Journal of Operational Research, 152*, 410–419.

Cui, K. Q. (2006a). Analysis of course and mechanism for industry units explosion. *M-Sized Nitrogenous Fertilizer Progress, 5*, 1–7.

Cui, K. Q. (2006b). Analysis of course and mechanism for industry units explosion. *M-Sized Nitrogenous Fertilizer Progress, 6*, 1–8.

Guimaraes, A. C. F., & Lapa, C. M. F. (2006). Hazard and operability study using approximate reasoning in light–water reactors passive systems. *Nuclear Engineering and Design, 236*, 1256–1263.

Jeong, K. S., Lee, D. G., Lee, K. W., & Lim, H. K. (2008). A qualitative identification and analysis of hazards, risks and operating procedures for a decommissioning safety assessment of a nuclear research reactor. *Annals of Nuclear Energy, 35*(10), 1954–1962.

Kim, M. C., & Seong, P. H. (2006). A computational method for probabilistic safety assessment of I&C systems and human operators in nuclear power plants. *Reliability Engineering & System Safety, 91*(5), 580–593.

Liao, S.-H. (2005). Expert system methodologies and applications—a decade review from 1995 to 2004. *Expert Systems with Applications, 28*, 93–103.

Venkat, V., Zhao, J. S., & Shankar, V. (2000). Intelligent system for HAZOP analysis of complex process plants. *Computer and Chemical Engineering, 24*, 2291–2302.

Wang, F., Gao, J. J., & Guo, K. (2009). A hazard and operability analysis method for the prevention of misoperations in the production of light magnesium carbonate. *Journal of Loss Prevention in the Process Industries, 22*(2), 237–243.

Wang, F., Gao, J. J., & Liu, W. B. (2008). Hazard and operability and explosion accidents analysis technology in chemical processes. *Journal of Chemical Industry and Engineering(China), 59*(12), 3184–3190.

Wu, C. G., Xia, T., & Zhang, B. K. (2003). The qualitative simulation based on deep knowledge model of signed directed graph. *Journal of System Simulation, 15*(10), 1351–1355.

Zhu, H. X., & Liu, J. Z. (2000). The design and trial operation of the residuum hydrotreating process. *Petroleum Refinery Engineering, 30*(7), 2–4.